ENERGY SPREAD COMPENSATION FOR MULTI-BUNCH LINAC OPERATION MODE

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Abstract

Higher wakefield gradients can be achieved by increasing the total beam charge which is passed through a dielectric-loaded structure and by reducing the transverse size of the beam. Currently, the Argonne AWA photoinjector operates with electron bunches of up to 100 nC and the goal is to raise the total beam charge to about 1000 nC and to improve the beam focusing to a few 100's microns transverse spot size. The increase of the beam charge can be done by superimposing electron bunches that fill up several consecutive RF buckets. Although the energy stored in a single 7-cell linac is by design large the multi-bunch operation with short bunch trains (≈ 10 ns) is still plagued by large energy spread due to significant beam loading effects. In this paper we present a technique intended to reduce the energy spread for a high charge bunch train by properly choosing the time delay between consecutive bunches. The simulations show that the energy spread can be lowered to about 2.8 % from about 6.0 % for a 10-bunch train of total charge 1000 nC and kinetic energy of about 70 MeV.

INTRODUCTION

Electron beam acceleration by wakefields produced when high charge bunches pass through dielectric loaded waveguides (DLW) is of special interest at Argonne Wakefield Accelerator (AWA) facility. Typically, the wakefields at AWA are produced by high charge (100 nC) 15 MeV drive beams and the transverse size of the DLW's is a few millimeters. During the recent years wakefield gradients of 100 MV/m have been reached and RF pulses of up to 44 MW have been generated at 7.8 GHz [1].

The amplitude of the wakefield scales linearly with the bunch charge and it is roughly inverse proportional with the transverse area of the DLW for both cylindrical [2, 3] and rectangular geometries [4]. The undergoing AWA upgrades [5, 6] aim at improving the beam focusing by increasing the energy from 15 MeV to about 75 MeV and at increasing the beam charge from 100 nC to about 1000 nC by operating the photoinjector in multi-bunch mode.

The simulations performed so far show that the increased beam energy would allow beam focusing to about 300 μm in the transverse spot size and the energy spread can be as low as 200 keV when the linac is operated in single-bunch mode. The only way to increase the beam charge to 1000 nC with the also improved high quantum efficiency $CsTe_2$ photocathode is to operate the linac in multi-bunch mode. For example, 10 consecutive rf buckets can be filled up with electron bunches of 100 nC each. The total length of the bunch train can be maintained relatively low, ≈ 10 ns, still comparable with the dominant wakefield wavelength.

The newly designed 7-cell accelerating structures operate at 1.3 GHz and can provide 11.8 MeV energy gain for 100 nC electron bunches. The energy stored in the cavity is by design fairly high 27.5 J and it decreases by 1.18 J after the passage of the first electron bunch. So, the following electron bunches "see" lower and lower field intensities and consequently are subjected to lower and lower accelerations. These beam-loading effects would play a significant role only in the multi-bunch operation because it is virtually impossible to compensate the decrease of the stored energy during a time interval of about 10 nanoseconds. Simulations show that the energy spread for a 10-bunch train can be as high as 6 % for the upgraded AWA photoinjector.

In this paper we present a technique which would lower the energy spread by slightly modifying the time-separation between consecutive electron bunches. Simulation results of the energy spread when the upgraded AWA photoinjector is operated in single and multi-bunch mode are also presented.

ENERGY SPREAD COMPENSATION

In the single-bunch operation mode the energy of each charged particle is generally correlated with its longitudinal position. Therefore, the energy spread can be easily reduced by simply operating off-crest at least one of the accelerating structures. By doing so only the correlated component of the energy spread can be removed and typically this comes at the expense of losing only a few percents of the total energy gain.

The energy spread is expected to be much larger in the case of multi-bunch operation. The reason is that during the passage of an electron bunch through an accelerating cavity the stored electromagnetic energy is depleted with the amount of the kinetic energy carried out by the bunch. Since the stored energy in the cavity cannot be replenished during the duration of the bunch train (≈ 10 ns) the accelerating field gradients decrease from bunch to bunch and so will the energy gain.

The energy stored in the accelerating standing wave

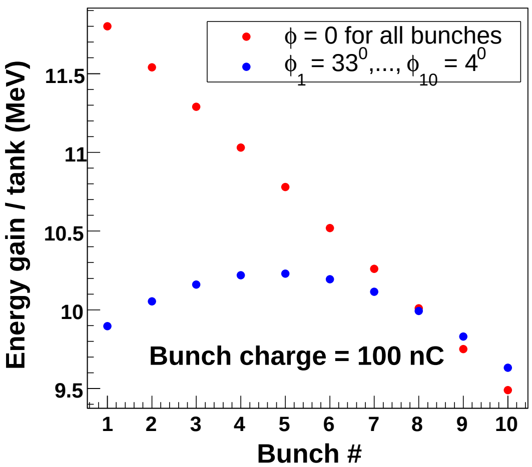


Figure 1: Energy gain for a train containing 10 electron bunches. The red bullets represent the energy gain when the time separation between consecutive bunches is one rf-period. The blue bullets represent the energy gain for the same train of bunches when the time separation is slightly higher (0.9%) than a rf-period. In this case the phase of the bunches ranges from 4^0 to 33^0

structure U_0 scales quadratically with the amplitude of the electric field E_0. Also, the energy gain ΔW_1 of the first electron bunch passing through the cavity is proportional to the amplitude of the electric field provided that effects like single bunch beam loading and bunch deceleration due to the wakefields are small. Since the time scale of the energy exchange between the cavity and the klystrons (several microseconds) is much longer than the duration of the bunch train (several nanoseconds) it is reasonable to assume that the electromagnetic energy stored in the cavity decreases with the amount of the kinetic energy carried out by the electron bunches.

The stored energy just before the pass of the n-th bunch U_{n-1}, the amplitude of the accelerating field E_{n-1} and the energy gain of the n-th bunch ΔW_n are related each other:

$$\begin{aligned} U_{n-1} &= C_1 \cdot E_{n-1}^2 \\ \Delta W_n &= C_2 \cdot E_{n-1} \end{aligned} \tag{1}$$

where C_1 and C_2 are constants depending on cavity geometry.

A recurrence equation for the n^{th}-bunch energy gain which involves only known quantities like the initial stored energy in the cavity (U_0) and the energy gain in single-bunch operation (ΔW_1) can be obtained from Eqns. 1:

$$\Delta W_n = \Delta W_{n-1} \sqrt{1 - \frac{\Delta W_1^2}{U_0 \Delta W_{n-1}}} \tag{2}$$

The energy gains for a train consisting of 10 pulses are evaluated with Eqn. 2 and shown in Fig. 1 with red bullets. The bunches are equally spaced in time and since all of them are synchronized with the maximum acceleration field the time separation between consecutive bunches is one rf-period (0.769 ns).

To partially compensate the energy spread due to the depletion of the stored energy, one may try to slightly increase (or decrease) the time separation between consecutive bunches. In this way the bunches are injected in the cavity at different phase-delays with respect to the on-crest operation. So, the contribution to energy gain due to larger field amplitudes can be partially compensated by a less favorable field-phase in the accelerating cavity. In the case of the AWA linac, the energy spread can be minimized if the phase separation between consecutive bunches is 3.2^0 and if the field phase for the first bunch is 33^0 from the maximum acceleration. The values of the energy gain for a 10-bunch train are shown with blue bullets in Fig. 1. In this way the energy spread can be lowered by at least two times compared with case of one rf-period bunch separation time.

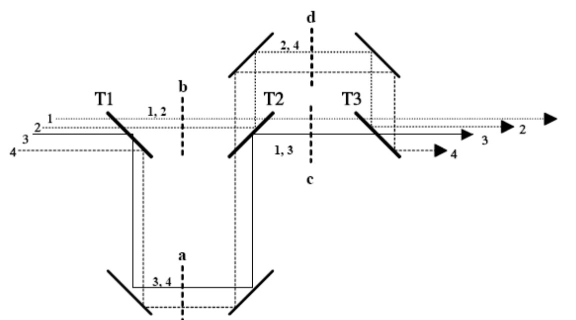


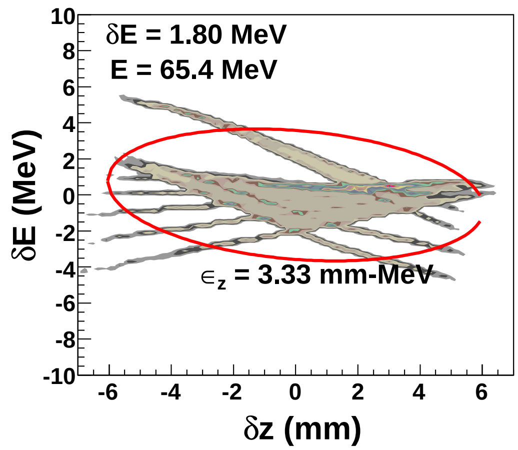
Figure 2: A single laser pulse enters from the left and exits the muti-splitter as 4 pulses separated by a geometry dependant time interval.

In the case of photoinjectors the most usual way to create trains of electron bunches is to split the laser beam into several smaller beams just before they reach the cathode. This can be done with a combination of high quality beam-splitters and mirrors. A simplified schematic drawing of the laser beam multi-splitter at AWA is shawn in Fig. 2. For practical purposes it is convenient to choose the same time delay between any consecutive electron bunches.

SIMULATIONS

The simulations of the upgraded AWA phototoinjector were performed with Impact-T [7] particle tracking code. Space charge forces and the short range transverse and longitudinal dipole wakefields [8] in the six linacs were taken into account.

In the single-bunch operation mode the largest component of the energy spread is correlated with the longitudinal position along the electron bunch. This ”correlated energy spread” can be entirely compensated by operating off-crest



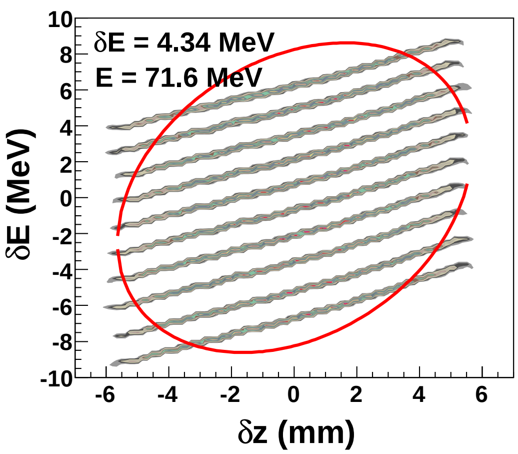


Figure 3: Top: energy versus longitudinal position plot in multi-bunch operation mode when the time separation between consecutive bunches is chosen such that the energy spread is minimum. Bottom: same plot when the time separation between consecutive bunches is just one rf-period. The longitudinal rms emittance ellipse is also plotted for both cases.

at least one of the six linacs. Our simulations show that the energy spread can be lowered from 1.2% rms to about 0.2% rms by operating all linacs at -14^0 from the phase corresponding to the maximum energy gain.

To simulate a multi-bunch operation mode, the tracking code must be run as many times as the number of bunches in the train. The reason is that the running conditions change from bunch to bunch. The phases of the external fields must change in all accelerating structures, and also the amplitude of these fields must be adjusted to make them consistent with the decrease of the energy stored in the cavities.

The results of the simulations for a 10-bunch train are shown in Fig. 3. The charge of each electron bunch is 100 nC. In the case when the time separation between consecutive bunches is one rf-period, the energy stored in each linac decreases from 27.5 J just before the pass of the first bunch to about 16.8 J after the tenth bunch passed through. This variation of the stored energy leads to significant variations of the kinetic energies gained by each bunch in the train (Fig. 3 bottom plot). Based on the model presented in this paper the linacs and gun phases were increased by 3.2 degrees from run to run and the amplitudes were calculated from Eqns. 1 and 2 with $U_0 = 27.5$ J, $E_0 = 13.4$ MV/m and $\Delta W_1 = 1.18$ J for each of the six linacs and $U_0 = 25.0$ J, $E_0 = 80.0$ MV/m and $\Delta W_1 = 0.833$ J for the gun. The results are shown in Fig. 3 top plot.

CONCLUSIONS

In this paper we present a model to partially compensate the energy spread in photonjector multi-bunch operation mode. We apply this model to estimate the energy spread for a 10-bunch train with a total charge of 1000 nC at the upgraded AWA photoinjector. When the time separation between bunches is just one rf-period the total energy gain is 71.6 MeV and energy spread (rms) is 4.3 MeV. When the algorithm presented in this paper is used the total energy gain is slightly lower 64.5 MeV, and the energy spread is significantly reduced to 1.8 MeV.

Even after optimization, the energy spread in the case of the multi-bunch operation mode is still significantly higher compared with the case of single-bunch operation (0.2%). Experiments dedicated to wakefield acceleration should benefit more from the large increase in the electron beam charge even if this comes with the disadvantage of a larger but manageable energy spread.

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